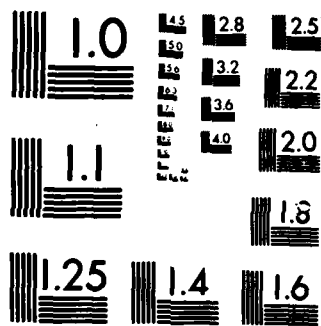END

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VOID/PORE DISTRIBUTIONS AND DUCTILE FRACTURE

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The effects of void or pore distributions on ductile fracture has been modeled experimentally. Pores or voids are physically modeled in two dimensions by both random and regular arrays of equi-sized holes drilled through the thickness of tensile specimens of 1100-0 Al sheet and 7075-T6 Al plate and sheet. Fracture strains as well as failure paths have been determined for different hole sizes, spacings, and area fractions. A statistical analysis of the data indicates that increasing the minimum hole spacing, which decreases the degree of hole clustering, increases both strength and ductility. Conversely, decreasing the hole size causes a minor increase in both strength and ductility. Increasing the rate of work hardening is beneficial to ductility in that a high strain hardening rate appears to increase the resistance to flow localization between holes. The results are discussed in terms of a fracture process which depends on shear localization between holes/voids and which is very sensitive to void/pore distributions.

INTRODUCTION

The presence of porosity is frequently a problem in alloys which have been cast, processed by powder metallurgy techniques, or welded. In addition, wrought alloys often contain large inclusions which crack and form voids at small strains when fracture of the matrix is still remote. In either instance, the deleterious influence of pores and/or voids on strength and especially tensile ductility is well known. It is also well established that the severity of the effect depends on the volume fraction of pores or void-nucleating inclusions (for example, see ref. 1); however, factors such as the inclusion size[2,3] and the degree of inclusion clustering[4] also influence fracture resistance. A difficulty in analyzing the influence of porosity or voiding on ductile fracture is that changes in one factor (for example the volume fraction of porosity) are usually accompanied by changes in other factors, such as the distributions of pore sizes, shapes, and spacings. Thus, an experimental separation of the individual effects of a pore/void microstructure on strength and fracture behavior do not exist.

The above situation is not confined to experiment; it also extends to theory. Nearly all theoretical analyses of fracture based on void growth and linking assume regular arrays of equi-sized holes or cavities.[5-11] Only Melander has attempted to analyze a random distribution of voids, but no experimental verification was attempted.[12-14]

Many previous studies, both experimental and theoretical, have used through-thickness holes as a two-dimensional analog of three-dimensional voids or pores.[5,8,11,13] In the present study, void distributions are modelled in two dimensions as arrays of holes whose positions are predicted using a random number generator. Experiments are conducted on arrays of equi-sized cylindrical holes in which (a) the area fraction of holes, (b) diameter of the

holes and (c) the minimum spacing between the holes (or degree of clustering) are controlled. The associated effects of these parameters on the deformation and fracture behavior are monitored. The study is based on two materials (1100 Al and 7075-T6 Al) of differing work-hardening rates which are tested under conditions of either plane stress or plane strain: (a) 1100-0 Al in the form of 1 mm sheet (plane stress deformation), (b) 7075-T6 Al also as 1 mm sheet and (c) 7075-T6 plate (6 mm thick) in which deformation between the holes is predominantly plane strain through the specimen thickness. The experimental design used is that of a 2^3 factorial in which 2 values are chosen for each of the three parameters[15]: area fraction of holes, hole size, and hole spacing. Specimens of the 7075 plate containing periodic arrays of holes are also tested for comparison with data from corresponding plate specimens containing random arrays. It should also be noted that the experiments do not attempt to explore a wide range of parameter values; rather they are intended as an initial study which indicates major trends. A more extensive study is currently in progress.[16]

This study thus serves as a basis for a qualitative model for the ductile fracture of materials containing voids or pores which takes into account the observed influence of void/hole distribution. In particular, the influence of hole size, hole spacing, and area fraction of holes (in a random array of holes) on ductile fracture may be understood in terms of sequence of stages which begins with strain concentrating near individual holes and ends with groups of holes/voids which have linked up and act as an imperfection to localize flow on an extended scale, causing failure. A theorectical analysis of the above process has been undertaken.[16]

<div align="center">EXPERIMENTAL TECHNIQUE</div>

Experimental Design

The experimental design used in the present study was based on a 2^3

factorial design, in which two values (or "levels") were chosen for each of three parameters ("factors") and experiments were performed for all combinations.[15] The design was chosen because it (a) required relatively few tests, (b) can indicate major trends, (c) can be easily analyzed and (d) can detect interactions or nonadditivity in the effects of the variables. The design cannot, however, explore a wide range of parameter values, and conclusions about the effects of a parameter on an outcome must be limited to the chosen range.[15] The parameters used to characterize the random arrays of cylindrical holes were: (1) hole diameter, D, (2) area fraction F, and (3) minimum hole spacing, S_m. The specific values chosen were D=1.2 or 2.0 mm, F=2.5 or 5.0%, and S_m=0.5 or 2.0 mm. The goal of this experiment was to determine the effects of D, S_m, and F on the tensile characteristics of percent elongation (e_f), yield stress (σ_y) and stress at maximum load (σ_m). To provide a statistical range of e_f, σ_y, and σ_m for a given set of D, F, and S_m parameters, three different array specimens were prepared for each set of D, F, and S_m values.

Generation of Random Arrays and Specimen Preparation

The random hole arrays were generated by a Fortran computer program containing a pseudo-random number generator using a program described elsewhere.[17] The holes are confined to the central 127 x 25 mm area of a tensile specimen with gauge dimensions of 32 x 143 mm. The minimum hole spacing, S_m, defined a circular region around each hole as measured from the hole surface, in which no other holes were allowed. Examples of two arrays having the same area fraction and hole size but different values of minimum hole spacing S_m are shown in Fig. 1. It should be noted that given the specimen size, the number of holes ranged from 27 to 145.

The three materials used were (1) 1100-0 Al sheet (1 mm thick), (2) 7075-T6 Al sheet (1 mm thick) and (3) 7075-T6 Al plate (6 mm thick). The
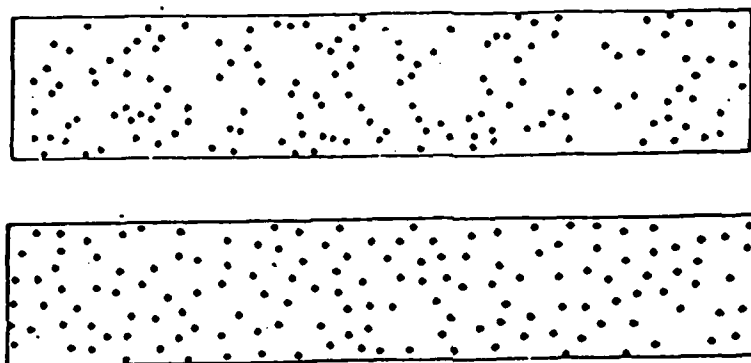
Figure 1. Examples of random hole arrays generated by the computer program showing two combinations of D, S_m and F: F=5%, and D=1.2 mm but in (a) S_m=0.5 mm while in (b) S_m=2.0 mm.

7075-T6 and 1100-0 aluminum alloys were chosen because of their differing work hardening exponents (n-0.10 for 7075-T6, and n=0.30 for 1100-0), and the two thicknesses were chosen to allow for different stress states between holes (plane stress for the sheet and plane strain for the plate). Specimen preparation was performed in a numerically controlled milling machine with the holes being drilled in the same random order that they were specified. After drilling, the 7075 specimens were reheat-treated to the T6 condition and the 1100 Al specimens were re-annealed. The average grain size was about 30μm for the 1100 Al and 35μm for the 7075 alloy..

Tensile testing was performed at room temperature at an engineering strain rate of $3x10^{-5}s^{-1}$. During the tests, macrophotographs were taken of the specimen to monitor specimen deformation, hole growth, and the fracture sequence.

RESULTS

Data obtained from the 72 tensile specimens were analyzed in a manner that would enable a determination of which of the parameters (hole size D, minimum holes spacing S_m, and/or area fraction of holes F) significantly influenced mechanical properties. The tensile properties of interest are percent elongation e_f, yield stress σ_y, and maximum tensile strength σ_m. As stated previously, conclusions as to the effects of D, S_m, and F on tensile behavior are limited to the specific ranges chosen for these parameters.

In order to analyze the data, a linear relationship is assumed between the properties (σ_y, σ_m, or e_f) and the hole distribution parameters (D, S_m, or F). Both "main" and "interactive" effects* are combined to form the linear

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* The term "main effect" refers to the independent influence of D, S_m or F on an experimental outcome, namely e_f, σ_y, or σ_m. The term "interactive" effect" denotes a nonadditivity or dependence of one parameter's influence on another.

model used in the analysis of the data obtained in this study:

$$y = \mu + \frac{a}{2} D + \frac{b}{2} S_m + \frac{c}{2} F + \frac{d}{2} DxS_m + \frac{e}{2} DxF + \frac{f}{2} S_m xF + \frac{g}{2} DxS_m xF \qquad (1)$$

In equation (1), y is the predicted value of e_f, σ_y, or σ_m and μ is the mean value obtained for e_f, σ_y, or σ_m from all specimens of one material. The coefficients a, b...g are the "estimated effects" of D, S_m ... $DxS_m xF$ respectively. The procedure to calculate estimated main and interactive effects of D, S_m, and F on e_f, σ_y, and σ_m is described elsewhere.[17]

In order to determine whether or not a property depends on a hole distribution parameter (in either a main or interactive manner), an analysis of variance was used with the alpha (or Type I) error[18] equal to 0.05. This usually translates such that if the estimated effect is much larger than the standard error (a pooled estimate of error based on the three replicates for each combination of D, S_m, and F), the effect is significant. In the model of equation (1), only the terms involving significant parameters are necessary for the prediction.

Effects of D, S_m, and F on Strength and Ductility

The main and interactive effects of the two levels of hole size D, minimum hole spacing S_m, and area fraction of holes F on tensile strength and ductility are listed in Tables I and II for the 1100 sheet, 7075 sheet, and 7075 plate. The table compares the values of the coefficients in Eq. 1 with the magnitude of standard errors which, because all the data for a given property are pooled for a material, have the same value. Whether or not a distribution parameter has a significant effect (i.e., as noted above, the alpha error is 0.05) on a property is indicated. An important advantage of

this analysis is that it allows an examination of a property to the <u>individual</u> effects of D, S_m, or F.

On the basis of the statistical analysis, Table I shows that in the case of 1100 Al sheet, only the minimum hole spacing has a significant effect on tensile strength with an increase of 4.8 MPa accompanying the increase of S_m from 0.5 to 2.0 mm. Analysis of yield strength data show a similar effect.[17] For both the 7075 sheet and plate, increasing S_m, decreasing D, and decreasing F all cause statistically significant increases in tensile strength. Thus at a given area fraction of holes in the 7075 materials, the specimen with the greatest strength is that with the smallest sized holes but which are spaced nearly uniformally.

The influence of D, S_m, and F on ductility is listed in Table II. For all three materials, increasing hole diameter decreases ductility at a given area fraction and hole spacing. Increasing minimum hole spacing (or decreasing the degree of clustering) has a strong effect in increasing ductility of 1100 and 7075 plate and a small effect in the 7075 sheet.* Within the range 2.5 to 5.0%, the area fraction of holes by itself does not significantly affect ductility, which is surprising. It should be noted that data obtained at smaller area fractions of holes do show the expected increase in ductility with a decreased area fraction of holes.[16]

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*The 7075 sheet data have very limited ductility (∿2%), thus making it difficult to determine statistical significant trends in changes of ductility.

TABLE I

Estimated Effects of D, S_m and F on the Ultimate Tensile Strength
of Al Specimens Containing Arrays of Holes.   Standard Errors are
Indicated.

Effect	Coefficient	Estimate + Standard Error (MPa)		
		1100 Sheet	7075 Sheet	7075 Plate
Mean	μ	76.2 ± 0.9	424.4 ± 2.5	493.7 ± 3.7
D	a	-2.8 ± 1.7	-22.3 ± 5.0*	-28.3 ± 7.5*
S	b	4.8 ± 1.7*	19.6 ± 5.0*	34.5 ± 7.5*
F	c	-2.3 ± 1.7	-27.9 ± 5.0*	-23.5 ± 7.5*
DxS_m	d	0.2 ± 1.7	- 5.4 ± 5.0	- 7.1 ± 7.5
DxF	e	-0.3 ± 1.7	7.0 ± 5.0	3.5 ± 7.5
S_mxF	f	1.2 ± 1.7	10.6 ± 5.0	5.8 ± 7.5
DxS_mxF	g	-1.9 ± 1.7	- 4.3 ± 5.0	- 4.3 ± 7.5

*Significant Effect

TABLE II

Estimated Effects of D, S_m and F on the Percent Elongation (e_f) of Al
Specimens Containing Arrays of Holes. Standard Errors are Indicated.

Effect	Coefficient	Estimate ± Standard Error (%)		
		1100 Sheet	7075 Sheet	7075 Plate
Mean		7.85 ± 0.19	1.32 ± 0.07	1.75 ± 0.08
D	a	−1.46 ± 0.38*	−0.34 ± 0.14*	−0.41 ± 0.16*
S	b	0.92 ± 0.38*	0.21 ± 0.14	0.78 ± 0.16*
F	c	−0.05 ± 0.38	−0.12 ± 0.14	0.05 ± 0.16
DxS_m	d	0.31 ± 0.38	− 0.11 ± 0.14	− 0.52 ± 0.16*
DxF	e	0.03 ± 0.38	0.13 ± 0.14	−0.10 ± 0.16
S_mxF	f	0.36 ± 0.38	0.10 ± 0.14	0.16 ± 0.16
DxS_mxF	g	0.34 ± 0.38	− 0.05 ± 0.14	−0.10 ± 0.16

*Significant Effect

Table V also shows that for the 7075 plate the DxS_m interaction is significant. Figure 2 illustrates the DxS_m interaction by plotting the average e_f at the two levels of S_m for each diameter. Note that the lines drawn between $S_m = 0.5$ mm and $S_m = 2.0$mm for each hole diameter are not parallel (as they would be if there were no DxS_m interaction). Specifically, the DxS_m interaction is such that the specimens containing smaller holes show a greater increase in e_f when the minimum spacing is increased. Although quantitative conclusions about the effects of D and S_m on percent elongation cannot be drawn due to the significant DxS_m interaction, the following trend may be deduced for the 7075-T6 plate: the effect of increasing S_m is to increase percent elongation, but the increase in e_f is much more pronounced when D=1.2 mm than when D=2.0 mm.

The results from the factorial experiment may be summarized as follows. First of all, the minimum hole spacing, or the degree to which clustering of holes is allowed, has a large influence on mechanical properties. When S_m has a significant influence on properties, in most cases its effect is to increase both strength and ductility when S_m is increased. Secondly, the hole diameter has a significant effect on e_f, σ_y, and σ_m in most cases; specifically the effect of increasing D is to decrease both strength and ductility. We also note that while other results show increasing F decreases ductility at F<2.5%,[16] this decrease is not statistically significant in the present data within the range of area fraction of holes from 2.5 to 5.0%.

Strain Localization and Hole Growth

Strain localization and hole growth was extensive in the ductile 1100 Al sheet, but limited in the 7075 sheet and plate. Fig. 3 shows a typical example of the dependence of local principal (true) strain, ϵ_1, across individual holes as a function of overall specimen (true) strain, ϵ_m for a
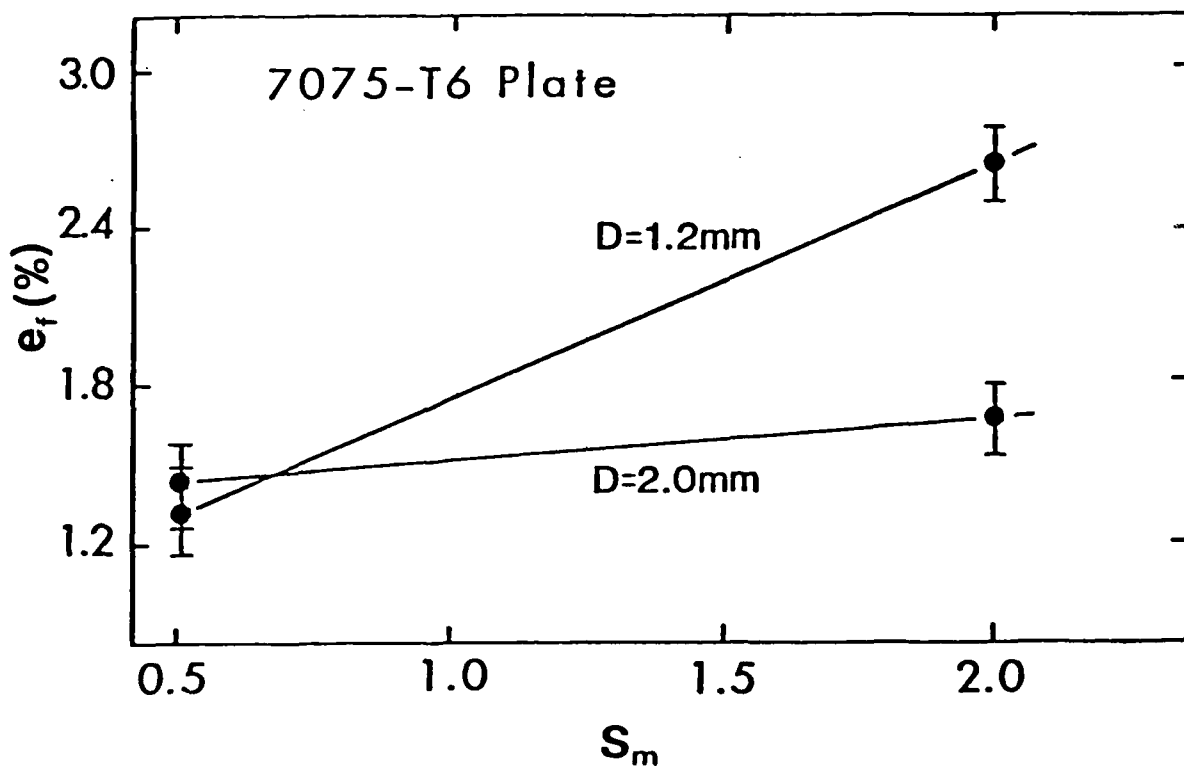
Figure 2. The influence of minimum hole spacing S_m on the elongation to failure of 7075-T6 plate specimens containing arrays of holes with diameters D of either 1.2 mm or 2.0 mm. Error bars indicate the standard error of an effect.
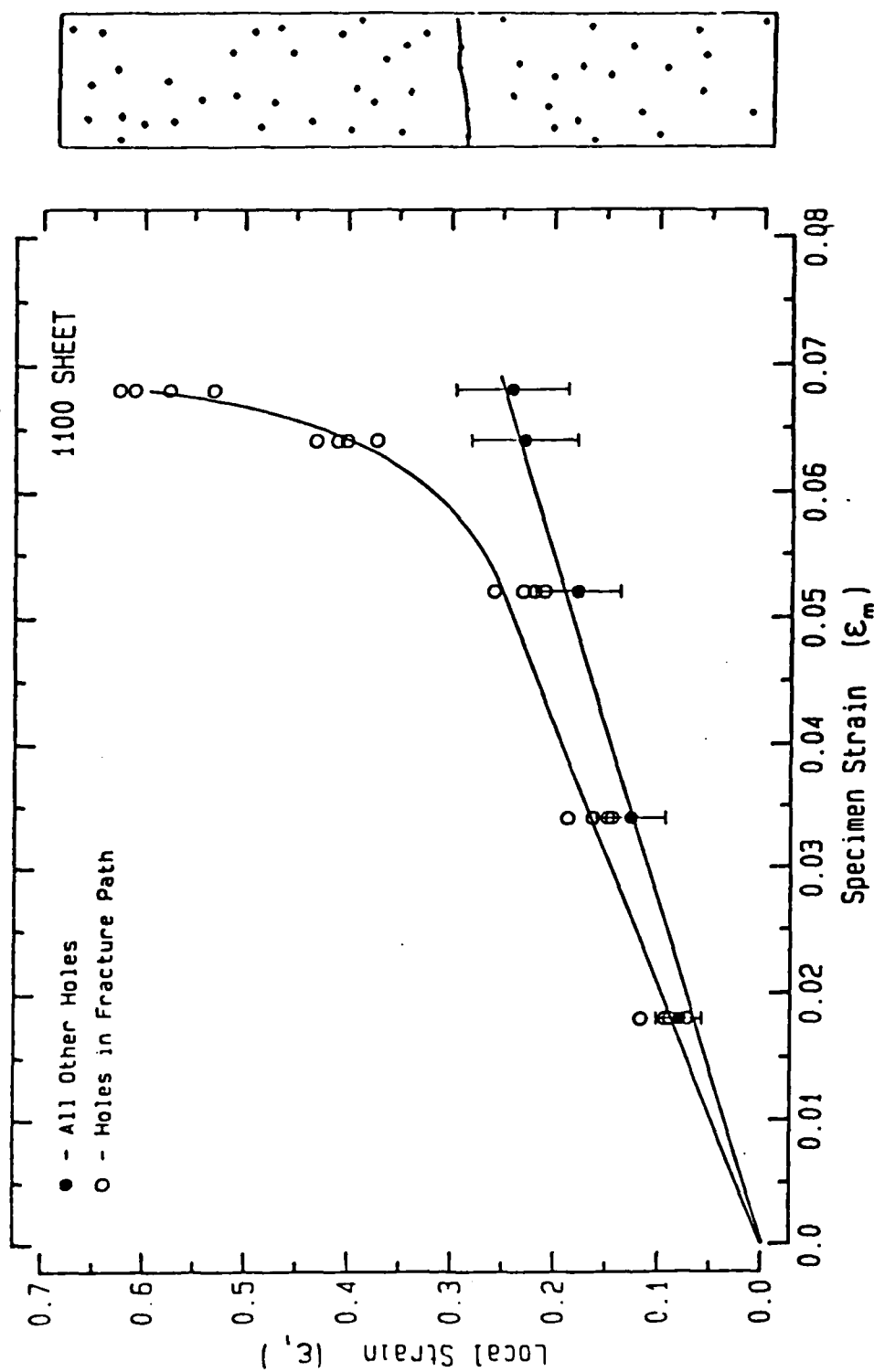
Figure 3. Local principal (true) strain, ε_1, across individual holes as a function of overall specimen (true) strain, ε_m, for the array shown in the 1100-0 sheet, (D=1.2 mm, S_m=2.0 mm. and F=5.0%). The differences in hole growth rates between holes in the fracture path and all other holes are indicated. Error bars represent one standard deviation.

single hole array in the 1100 sheet. Similar but not as extensive data are obtained for the less ductile 7075 sheet and plate. Two important trends are especially evident. First, local strain (as measured by hole growth) increases linearly with the macroscopic tensile strain. Furthermore, the holes tend to concentrate strain such that the accumulation of local strain is linearly related to the macroscopic strain, being about four times the macroscopic strain. The present data also show that the major axes of the holes increase linearly with strain, as expected by theory.[5] Secondly, the hole growth data for the ductile 1100 Al show that flow localization occurs among most but not all of the holes in the eventual fracture path, even at small strains ($\epsilon \cong .02$). These "special" holes grow at a faster rate, and fracture is associated with a strain localization process in which strain is concentrated along the fracture path at a rate which accelerates with strain.

Macroscopic Observations of the Deformation and Fracture Process

The strain localization process near and between closely spaced holes is readily evident in macrophotographic observations made of the deformation and fracture sequence. As shown in Fig. 4 for 7075 Al plate, the deformation sequence involves (1) strain concentrating near isolated holes at small strains, (2) strain localization between closely spaced holes oriented at ∿45° to the tensile axis for the plate (and ∿90° to tensile axis for the sheets), and (3) fracture of ligaments between closely spaced, preferentially oriented holes. The first stage is consistent with plastic zone development near holes [19,20] while the second is a consequence of plastic zone overlap between closely spaced, preferentially oriented holes. For plate specimens, this latter stage should occur preferentially for holes oriented such that plastic zones at 45° to the stress axis can overlap.[20,21] A third stage of the deformation and fracture process is also evident in Fig. 4; this involves ligament fracture and further strain localization near a pair of linked holes.
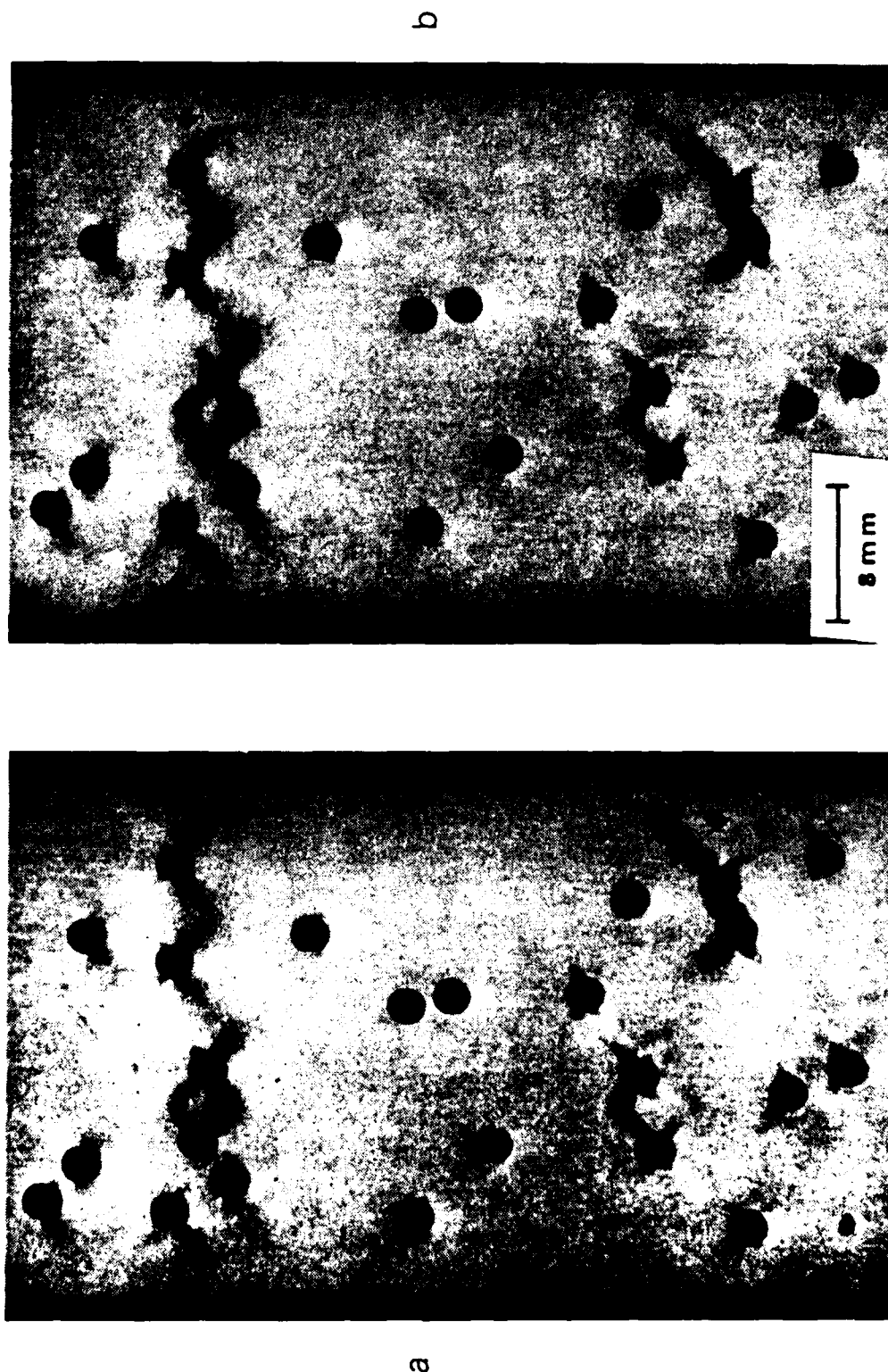
Figure 4. Macrophotographs showing (a) the formation of an isolated "linked" hole and (b) formation of a second pair of linked holes and final fracture path in the upper portion f the figure. The specimen is a 7075 plate (D=2.0 mm, S_m=0.5 mm, F=5.0%).

In this case, linking creates an elliptical "superhole" which further intensifies the local plastic zones. The enhanced plastic zone is now able to interact with a third hole if one is favorably located. Thus, the strain localization and hole linking process "percolates" throughout the specimen as macroscopic straining occurs.

Regular Arrays

As a basis for comparison, three regular arrays (square, diagonal, and triagonal) of holes were prepared in 7075 plate specimens at F=5.0% and D=1.2 mm. While all of the regular arrays show similar yield strengths and ductilities, only the diagonal array failed at ∿45° to the stress axis, which was near the preferred macroscopic failure plane for the random hole arrays in the plate. Data for the diagonal regular array are compared in Fig. 5 with the corresponding random array data for two minimum hole spacings: S_m=0.5 and 2.0 mm. As seen in Fig. 5, the regular array has a slightly higher yield strength and a markedly higher ductility. This contradicts Melander's conclusion, which is based on a theoretical analysis of two different distances between voids, that the critical strain to fracture increases with the difference in void spacing.[13] A consequence of such a conclusion is that the material with a random array of voids should be more ductile than a material with a regular array, which contradicts the data in Fig. 5.

Fig. 5 is also consistent with the earlier conclusion that minimum hole spacing is a significant factor in determining ductility. The data in Fig. 5 indicate that for a given area fraction (5%) and hole size (2.0 mm), increasing minimum hole spacing increases ductility. This conclusion is further confirmed by tensile tests of specimens with "random" hole arrays approaching those of the regular arrays.[16]
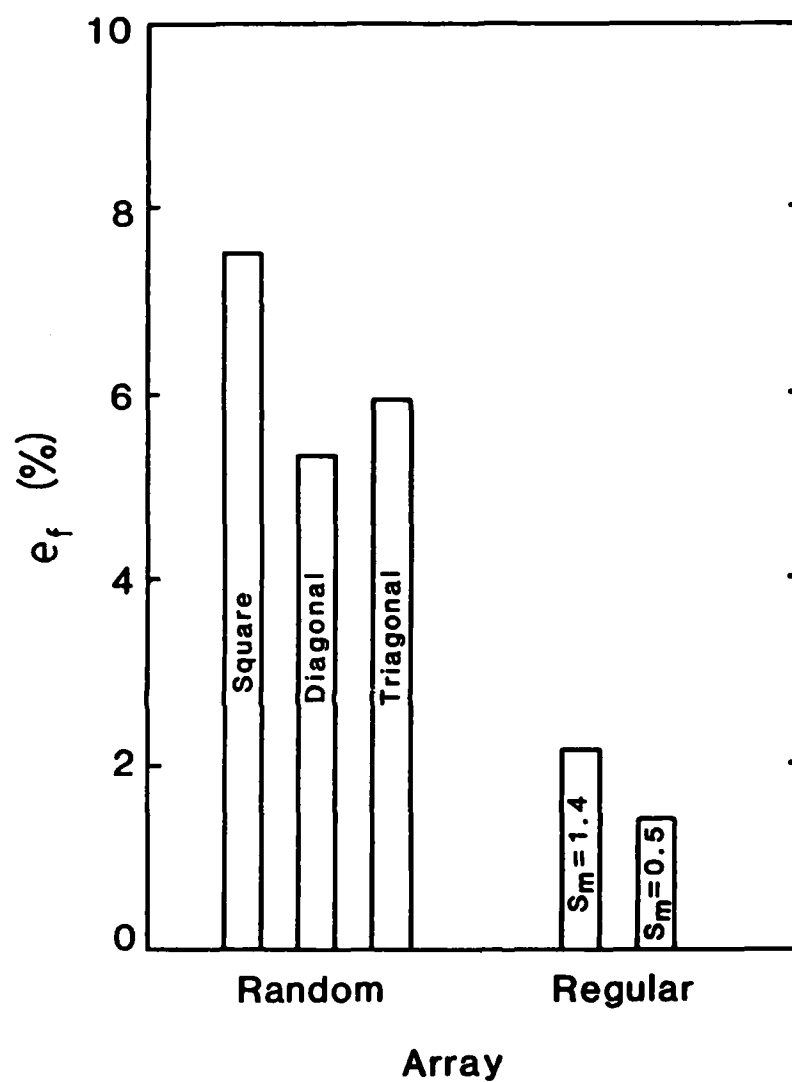
Figure 5. The elongation to failure of 7075 Al plate specimens containing 5% holes in either regular or random arrays.

DISCUSSION

The data indicate several significant observations. First and most pronounced, the value of the minimum hole spacing S_m, which indicates the degree of clustering among holes, has a strong influence on percent elongation, yield stress and maximum tensile strength. If clustering is inhibited by increasing S_m, ductility as well as strength increase. Secondly, the diameter of the holes, D, also has a important effect on mechanical behavior. Decreases in e_f, σ_y, and/or σ_m occur when hole size is increased. Thirdly, while area fraction of holes decreases strength, the individual effect of F on ductility is negligible in the range 2.5 to 5.0%. Fourth, hole extention occurs for nearly all holes at a rate linear with strain, but strain localization (or accelerated hole growth) occurs among some of the holes along the eventual fracture surface. Fifth, macroscopic observation indicate strain concentrating near holes and subsequently localizing between closely spaced holes at preferred orientations to the stress axis. Sixth, while specimens containing regular arrays of holes also show flow localization between holes, the process is sufficiently retarded such that 7075 plate specimens with regular arrays exhibit roughly three times higher elongation to failure than the random arrays tested with the same area fraction and size of holes. Seventh and lastly, the area fraction of holes on the fracture surface are roughly eight to ten times the original nominal area fractions. This ratio is very similar to that observed on the fracture surfaces of specimens containing porosity.[22]

In order to understand the above observations, the flow and fracture of these materials, as well as materials containing voids or pores, is proposed to obey the following sequence: (1) slip initiates nonuniformly near holes (or voids/pores), (2) flow is localized on planes of high shear stress between closely spaced pairs or clusters of holes/voids/pores, (3) an individual

ligament between two holes fractures and creates a large ellipsoidal hole which, due to its increased size and eccentric shape tends to further localize flow along its major axis, (4) a statistical problem arises as to whether or not a third hole/void/pore exists in a favorable position to the large elliptical cavity; if a third void is favorably located, successive flow localization and ligament fracture occurs, but if not, deformation of the entire material continues until another pair of voids/pores link-up by ligament fracture, initiating the above sequence, and (5) a group of voids or pores which have linked up cause a large imperfection; this in turn causes further localization over a much larger scale and finally, the material fractures along a path of high hole content.

Stage one involves initiation of nonuniform slip around voids/pores. Upon local yielding voids will elongate and grow to form ellipsoids with and accompanying development of plastic zones whose shape and orientation depend on stress state. In plane strain, as shown in Fig. 4, four lobes of plasticity emanate radially from individual holes with the band of maximum strain occurring at roughly 45° to the tensile axis.[20] The diffuseness of plastic flow within the deformation zones is a sensitive function of work hardening[20]; thus a 1100-0 Al plate would have a diffuse plastic zone and would be much more resistant to flow localization than the 7075 alloy. In the plane stress case, through-thickness slip dominates and the resultant plastic zones appear two broad lobes on two transverse sides of a hole. The orientation of the deformation zones reflects the localization of strain along planes of maximum shear stress which are at 45° angles between holes in the plate and inclines 45° through the thickness of the sheet. As expected by theory,[19,20] the size of the plastic zones was observed to be dependent on the hole size with larger holes showing larger plastic zones. The zones around both the 1.2 and 2.0 mm holes in the 1100 sheet were measured in both cases

the intense plastic zone regions scaled with hole size, being approximately one half the diameter of the holes.

The second stage in the proposed fracture sequence, namely the localization of flow between a pair of voids, occurs when the plastic zones from two neighboring voids overlap. This stage should be dependent on the hole/void spacing, size, and orientation as well as the work hardening of the alloy. Larger voids, which have larger plastic zones, are able to localize strain over larger ligaments between holes than smaller ones, especially if located within a material of low strain hardening (i.e., the 7075). In addition, the closer the holes/voids are to each other (small S_m values), the more likely it is that their plastic zones will overlap and thus intensify the localization of flow. Whether or not plastic zones will overlap also depends upon the relative orientation of two holes or voids. For the plate deformation, localization occurs most readily when adjacent holes are oriented roughly 45° to the tensile axis while in the sheet localization is facilitated by closely spaced hole roughly normal to the stress axis. If a pair or cluster of holes (or voids) are closely spaced and oriented for plastic zone overlap, flow localization is readily evident by enhanced hole growth, even at comparatively small strains (see Fig. 3).

Stage 3 in the fracture process, which is the failure of a ligament between a pair of voids, is the direct result of Stage 2. In order for fracture to occur between voids, a critical stress and/or strain must be reached. For example, Fig. 3 indicates failure of the ligaments in the 1100 sheet at $\varepsilon_{1f}=0.6$, while similar data for the 7075 plate indicate $\varepsilon_{1f}=0.2$. It is proposed that, in the present case, fracture occurs along planes of high shear strain between closely spaced, preferentially oriented holes/voids. In the 7075 plate specimens, the average angle of inclination of the first failed ligament was approximately 40° ($\pm$ 17°), and the first ligament orientation

preferred by both sheet materials was closer to the horizontal (at an average angle of about 15°) across the specimen width but inclined approximately 45° through the thickness. Thus, the ligaments between holes in both plate and sheet fail on planes oriented closely to maximum shear stress planes. The hole size, spacing, and orientation all influence the macroscopic strain required for failure of the ligament since all of these parameters affect the overlapping of plastic zones and subsequent shear localization.

The bulk porosity level should not have a strong influence on Stages 1-3 since these involve shear localization and failure between only a pair of voids. In the present study, each specimen contains a sufficient number of randomly oriented holes (recall that $F \gtrsim 2.5\%$) so that even at different bulk hole/porosity levels, each has at least one pair of closely spaced and ideally oriented holes/voids. Thus we do not expect a strong dependence of area fraction of holes F on at least the initial stages of fracture which include failure of the first ligaments.

Failure of the first ligament creates a large elliptical hole/void whose major axis is no longer parallel to the tensile direction and whose increased size and eccentric shape intensify flow localization especially if its major axis lies in the maximum shear stress plane. As with a single hole,[20] it is expected that flow localization near a linked pair of holes in a material of low strain hardening will be more intense than in a high work hardening material. The formation of a large, isolated elliptical hole formed by the linking of a pair of smaller holes is illustrated in the lower portion of Fig. 4 for plane-strain tension. In the present study, pairs of these linked holes were observed in several instances (in all three materials) at locations remote from the final fracture path.

The fourth stage of fracture requires that a third void or hole be oriented in such a manner that its plastic zones overlap with those of the

linked, elliptical hole/void. The probability of finding such a hole should depend on all three of the random distribution parameters varied in this study. Clearly, the higher the bulk porosity level (F), the greater the probability of finding a void in the region around the joined pair of holes/voids. The smaller the minimum spacing, S_m (or the higher degree of clustering), the greater are the chances of having a third hole close enough to interact with the "pair" hole. The hole or void diameter again affects the size of the plastic zone around the third hole so that a larger third hole need not be as close to the joined elliptical hole as a smaller one for overlapping of plastic zones to occur. If a third hole/void is not located for easy link-up with the large elliptical hole/void, as is the case in Fig. 4, the material as a whole will deform until another pair of holes link-up and again a preferential third hole is sought. In other words, Stages two and three may be repeated many times before stage four occurs, increasing the ductility of the material. For example, photographs of Fig. 4 show that extension of the 7075 plate specimen continued after one ligament had failed because a third hole was not favorably positioned for link up. Failure in the specimen shown in Fig. 4 eventually occurs in the upper portion of the specimen as denoted by the arrows.

In Stage five, a group of holes/voids which have linked up form an imperfection which, acting as a region of weakness, further localizes deformation over a much larger scale until the material finally fails. Such a localization process is readily evident in the hole growth data in Fig. 3. The imperfection that is formed consists of a path of high hole/void content. In the present study, the fact that failure of ligaments between three holes was never observed remote from the final fracture surface indicates that the imperfection consists of three linked holes plus a zig-zag path of high hole

content extending to the specimen surface. As in a study of the fracture of porous Ti and Ti-6Al-4V,[22] this results in fracture surface which contains an area fraction of holes/voids which is 8-10 times the bulk density.

The current observation that area fraction of holes F has a negligible effect on ductility in the range F=2.5-5.0% may now be understood. If in the present study the linking of three holes is sufficient to create a significant imperfection and to percolate fracture, then ductility is roughly equal to the strain required to link three holes. Given the number of holes present in the specimens, each contains at least three holes which are closely spaced and properly oriented to link at strains which are statistically similar. Thus area fraction effects on ductility are minimized in the present tests. In a material containing porosity or voids on a microscopic scale, the number or pores/voids which must link to create the imperfection will be much larger than three. As a result, the probability of linking a sufficient number will be greater a high pore/void contents. Thus, the present observations and qualitative model are quite consistent with the well established loss of ductility with increasing pore content.[1] [note: The present study also clearly suggests that at least some of the observed effects of pore content are actually related to changes in pore size or spacing.]

In the fracture sequence proposed, the latter four stages are strongly dependent on the distribution of voids or pores, with interaction between closely-spaced, preferentially-oriented voids being critical in the link-up process. For this reason it is not appropriate to assume that equi-spaced holes in regular patterns approximate fracture in a real material containing randomly oriented voids/pores. For example, present tests of 7075 plate specimens with square, hexagonal and diagonal arrays of holes show that the regularly arrayed specimens fail at overall strains of 3-4 times those of the randomly arrayed specimens, even though, (in the case of the diagonal array), the holes were ideally oriented along 45° maximum shear planes.

The rate at which Stage five (the development void-induced imperfection) proceeds depends upon the material properties, particularly the strain-hardening exponent n, as expected from analysis.[23, 24] Linking of holes/voids in the 7075 sheet and plate specimens occurred very rapidly, while in the 1100 sheet it occurred gradually, with each ligament deforming to a knife edge. The final fracture path, however, is clearly dependent on the state of stress between voids. In most cases both sheet materials chose nearly identical holes paths for failure but a much different failure path occurs in the plate specimens.[17] It should be noted that in both sheet and plate, the fracture path remains one which is characterized by high shear stresses on planes inclined across the width (plane strain/plate) or through the thickness (plane stress/sheet). Thus it is concluded that the localization process is shear instability process triggered by the linking of critical number of holes/voids (three in the present study) and a path of high hole content.

SUMMARY

The experimental observations in the present study lead to the following conclusions:

(1) The value of the minimum hole spacing, S_m, which indicates the degree of clustering among holes, has a strong influence on both ductility and yield/tensile strength. If clustering is inhibited by increasing S_m, ductility as well as strength increase.

(2) The diameter of the holes D also has the effect that decreases in e_f, σ_y and/or σ_m occur when hole size is increased.

(3) While strength decreases with increasing area fraction of holes F, it has a negligible effect on percent elongation in the range 2.5% to 5.0% for all three materials tested.

(4)   Hole extension in the tensile direction occurs at a rate which is
      linear with strain. These data also show that strain-induced
      accelerated hole growth occurs among some but not all of the holes
      in the eventual fracture path.

(5)   Macroscopic observations show that, upon deformation, strain
      localizes along a plane of maximum shear stress between either a
      pair or groups of holes which are both closely spaced and
      preferentially oriented with respect to the stress axis. These
      eventually form the fracture path as the flow localization causes
      ligaments to fail.

(6)   The final fracture path for a particular array of holes depends on
      the stress state between the holes (or the orientation of the
      maximum shear stress planes). The two sheet materials tested in
      this study (1100-0 Al and 7075-T6 Al) showed identical fracture
      paths for many of the hole arrays, whereas the plate material
      (7075-T6 Al) usually chose a much different fracture path. The area
      fractions of holes on the fracture surfaces are on the average
      eight to ten times the original nominal area fractions.

(7)   The 7075 plate specimens with regular arrays of holes exhibit three
      to four times more ductility than those containing random arrays for
      the same hole size and area fraction.

These experimental observations indicate that the the flow and ductile
fracture of materials containing voids or pores consists of the following
stages:

I.   Slip initiates near individual holes (or voids/pores) as plastic
      zones form.

II.   Flow is localized on planes of high shear stress between closely
      spaced and favorably oriented holes.

III. An individual ligament between two holes fractures and creates a large elliptical hole which, due to its increased size and eccentric shape, tends to further localizes flow along its major axis.

IV. A statistical problem arises as to whether or not a third hole exists in a favorable position with respect to the large elliptical cavity. If a third hole is favorably located, successive flow localization and ligament fracture occurs, but if not, deformation of the entire material continues until another pair of holes/voids link up by ligament fracture, initiating the above sequence.

V. A group of holes (voids/pores) which have linked create a large imperfection. This in turn causes further localization and subsequently a shear instability over a much larger scale and finally, the material fractures.

The above sequence is sensitive to (a) minimum spacing between holes (which strongly affects shear localization between holes), (b) hole size (which controls plastic zone size and therefore the physical scale of the shear localization possible), (c) strain hardening (which tends to diffuse localization and delay the shear instabilities) and (d) in a material containing a large number of pores or microvoids, the area fraction of pores/voids (which affects the strain necessary to link sufficient voids/pores to create the critical imperfection).

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